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Safety and Environmental Aspects of Fusion Reactors*

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Abstract

Fusion is examined against the yardstick of fission technology with respect to inventories of radioactivity (and associated Biological Hazard Potentials), routine emissions, accident pathways and consequences, radioactive-waste management, and misuse of nuclear materials. Based on conceptual designs of Tokamak fusion reactors with stainless steel structure and tritium inventories of 10 kg per thermal gigawatt, the apparent advantage of fusion is 1 to 2 orders of magnitude in most indices of radiological hazards. Fusion's advantage is 2 to 5 orders of magnitude in comparing damage potential of intentional airborne dispersal of tritium and plutonium, but nonexistent in comparing medium-term radwaste hazard potential (1000 to 100,000 years) and intentional waterborne dispersal of tritium and plutonium. Fusion appears to have some qualitative advantages with respect to accident pathways and safeguards considerations. Fusion has the theoretical potential for improvements of 1 to 2 additional orders of magnitude in short-term BHPs and 3 orders of magnitude and more in radwaste BHPs after 10 years if vanadium-titanium alloy can be used in place of stainless steel in the reactor structure. Other important unresolved questions are how much the inventory of tritium can be reduced by ingenious design, and what fraction of a fusion reactor's activation products could be volatilized and released in a severe accident such as a lithium fire. Overall, fusion's potential advantages are appreciable but not automatic--it will require early and sustained attention to environmental characteristics to avoid losing some of the potential advantages in pursuit of other goals.

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Introduction

The traditional rationale for developing fusion as an energy source has been that it will be inexhaustible, cheap, clean, and safe. On any interesting time scale, however, sunlight and fission breeder reactors are also "inexhaustible" energy sources. Furthermore, the high construction costs of fusion reactors probably will more than offset the cheapness of the fuel: it now seems unlikely that fusion will be cheaper than fission and it may not be cheaper than solar. Thus the case for fusion rests, more strongly than is commonly supposed, upon whether it enjoys real advantages over competing energy sources with respect to environment and safety. This paper examines fusion's environmental and safety characteristics against the more familiar yardstick of those of fission (1). Fusion's early stage of technological development makes such an evaluation difficult, but the attempt is worthwhile because there is still time to steer fusion-reactor design in the direction of minimizing potential hazards that are uncovered.

Environmental and safety characteristics of conceptual fusion-reactor designs have been surveyed in a number of earlier reviews (for example, 2-7). Both fusion technology and environmental assessment are rapidl[illegible]g fields, however, which makes frequent re-examination of th[illegible]e of information on environmental aspects o[illegible]ile. This review has benefited from better information on neutron activation in fusion-reactor blankets than was available earlier, from estimates of tritium inventories that are probably more realistic than earlier values, from the general continuing increase in realism and sophistication evident in conceptual fusion-reactor designs under development around the world, and from recent work in fission-reactor safety analysis (such as the Reactor Safety Study of the U.S. Nuclear Regulatory Commission).

Environmental effects, broadly defined, originate in many stages of the fuel cycles of modern energy supply (for example, exploration, extraction, processing, transportation, conversion, and end use); they take many forms (for example, routine effluents, accidents, other environmental transformations, resource consumption, and social disruptions); and the damages are felt by a variety of kinds of victims in a variety of ways (for example, occupational death and disease, direct health damage to members of the public now alive and in future generations, damage to economic goods and services such as buildings and tourism, damage to environmental goods and services such as climate regulation and nutrient cycling, and generation of aggravations and tensions within and between nations) (8). I will confine my attention here, however, to a narrower subset of environmental issues - namely, those issues that are generic to nuclear energy sources and that are the subject of close scrutiny and often controversy today in the case of nuclear fission power. These are: (a) occupational and public radiation exposure as a consequence of the routine operation of nuclear fuel cycles (excluding storage or disposal of long-lived radioactive wastes); (b) nonroutine releases of radioactivity from reactors or other fuel-cycle facilities owing to accidents or sabotage (but again excluding long-term waste management); (c) the problem of the long-lived radioactive wastes; and (d) the use of nuclear materials produced in commercial facilities for weapons, by nations or subnational groups. (The numbering is not meant to imply an order of importance). Information on some of the environmental issues I will not consider here - such as land disturbance in fuel extraction, thermal discharges, and demands on nonfuel minerals - is available in several earlier reviews (e.g., 2, 6, 9).

The present review is based mainly on the D-T fusion fuel cycle using magnetic confinement. Some but not all of the results are specific to Tokamaks, on which the most extensive conceptual-design literature happens to be available. A few comments about advanced fusion fuel cycles are made at the end.

Radioactive Inventories and Hazard Potentials

The first step in evaluating hazards from either routine or nonroutine releases of radioactivity is to determine how much and what kinds of radioactivity the system in question contains. Table 1 compares the inventories in megacuries per gigawatt-electric (GWe) of capacity in Liquid Metal Fast Breeder Reactors (LMFBR) and in two conceptual Controlled Thermonuclear Reactors (CTR). All the reactors are assumed to have a thermal-to-electric conversion efficiency of 40 percent, so 1 GWe corresponds to 2.5 gigawatts-thermal (GWt). The CTRs are liquid-lithium cooled Tokamaks identical except for the structural materials exposed to neutrons: one uses 316 stainless steel (316SS); the other uses an alloy of 84% (atomic) vanadium and 16% titanium (V-Ti). The specific CTR design is the University of Wisconsin Tokamak UWMAK-I (10). The LMFBR is a scale-up of the German-Belgian-Dutch SNR-300 (11).

The major components of the CTR tritium inventory are (a) the tritium injection, collection, and purification systems (3 kg T per GWt); (b) the breeding medium and separation unit (1 kg/GWt); and (c) storage and emergency inventory (6 kg/GWt), for a total of 10 kg or 100 megacuries per GWt. This is a somewhat larger figure than these cited in most earlier work; it arises from assuming 5% burn-up of T per pass through the plasma, a hold-up time of 1 day in the tritium circuit, and a reserve of 2 days' supply of T to keep the reactor running during repairs on the fuel handling system. About [illegible]4 percent of the initial activation in the 316 SS CTR blanket (2 year operation at 1.25 MW/m^2 neutron wall loading) is in five isotopes: 27.8 day Cr-51 (250 MCi), 303 day Mn-54 (134 MCi), 2.58 hour Mn-56 (880 MCi), 2.6 year Fe-55 (488 MCi), and 71.3 day Co-58 (225 MCi). The initial activation in the V-Ti blanket (same loading as for 316 SS) is mostly 3.75 minute V-52 (2565 MCi), 5.8 minute Ti-51 (198 MCi) and 1.83 day Sc-48 (96 MCi). The coolant activation figures are for liquid lithium and arise from impurities (principally [illegible], Cl, Na, and K) and corrosion products.

The fission product activity in an LMFBR is distributed among a large array of isotopes; among the volatile ones (comparable in some sense to tritium), the iodines dominate (555 MCi in I-131 through I-135). Nearly 80 percent of the initial structural activation is Mn-54 (18 MCi), Mn-56 (22 MCi) and Co-58 (38 MCi). The coolant activation is 15 hour Na-2[illegible] (108 MCi) and 2.6 year Na-24 (1 MCi). The initial actinide activity is dominated by 23 minute U-239 and 2.4 day Np-239 (17[illegible] MCi each). The biggest actinide contributor at 30 days is Pu-241 (16 MCi).

The comparisons in Table I are somewhat distorted in favor of fission, by virtue of the neglect of inventories of radioactive fuels in parts of the fuel cycle other than the reactor itself. The plutonium activity in an LMFBR fuel cycle outside the reactor is about 15 percent of what is in the reactor (12); tritium, by contrast, is recycled within the fusion reactor plant and the inventory shown in Table I includes the contents of this internal cycle.

A better measure of hazard than radioactivity in curies is the Biological Hazard Potential (BHP), obtained by dividing the inventory of an isotope by its Maximum Permissible Concentration (MPC) or Recommended Concentration

Guideline and summing over all isotopes present. With MPC in curies per cubic meter of air or water, the resulting BHP represents the volume of air or water that would be needed to dilute the inventory to the permissible level. Table 2 shows the BHPs, for dilution in air in unrestricted areas, corresponding to the inventories of radioactivity in the LMFBR and in the 316SS and V-Ti CTRs.

The MPCs used to derive these numbers are those in force in the United States at the end of 1975 (11). When values for soluble and insoluble forms of an isotope differ, the lower MPC - giving the higher BHP - has been used here. This widely used procedure may distort certain comparisons. For example, the MPCs for soluble plutonium and other alpha emitters are generally much lower than for insoluble forms, but these elements exist in reactors as highly insoluble oxides. If they remain in that form under accident conditions, then use of the MPCs for the soluble form in BHP calculations overstates the contribution of the actinides. (If the actinides in the LMFBR calculation in Table 2 were all assumed insoluble, their contribution to the BHP would fall from 11,500 million km^3 to 1700 million km^3.) On the other hand, the MPC for the soluble form is appropriate to that part of the entire-fuel cycle's plutonium inventory that is stored as the nitrate.

The MPC used to compute the BHP of tritium in Table 2 is for tritiated water (HTO or T_2O), a value 200 times lower than that for tritium gas (HT or T_2). To the extent that any of the tritium inventory is gaseous tritium and might remain so upon release, the figure given in Table 2 overstates the hazard. A significant part of the tritium released in routine operations might well be tritium gas, and the characteristic time for oxidation in the environment is very long - it is on the order of days, even in the presence of catalysts. The largest accidents, on the other hand, are probably those involving fires, in such a case, it is likely that much of the tritium released would be in the oxide form.

With the foregoing caveats, one can conclude tentatively from Table 2 that the relative hazard represented by the tritium inventory in the conceptual CTRs is about three orders of magnitude smaller than that represented by the fission products in LMFBRs of the same generating capacity, and that the activation products in the CTRs represent a relative hazard one to two orders of magnitude smaller than that represented by the actinides in the LMFBR. (Activation in the V-Ti CTR is approximately an order of magnitude less than that in 316SS CTR and comparable to activation in the LMFBR.)

Radiation Exposure from Routine Operations

The principal radioactive substance that will be released during routine operation of fusion power plants is tritium. Its considerable inventory, combined with a propensity to diffuse through certain metals and the difficulty of separating tritiated water from ordinary water, poses non-negligible problems for fusion-reactor designers.

Tritium may enter the body through inhalation, through skin absorption, and through ingestion in food and water. It is effective only as an internal emitter, since its soft beta radiation (18 keV maximum, 5.7 keV average) cannot penetrate the dead layer of the skin. Values found in the literature for the whole-body dose commitment resulting from intake of a curie of tritium as the oxide vary from 40 to 260 rem, but the higher values follow from assumptions now regarded as inappropriate (14). A reasonable value, based on quality factor (QF) of 1.0, biological half-life in the human body of 1[illegible] days, and an upward correction of 20% for binding of T in organic compounds in tissue, is [illegible] rem per curie (15). Based on this figure, the concentration of HTO in air that leads to an adult exposure via inhalation and skin absorption of [illegible] mrem per yr is [illegible] μCi/m³ (about twice the MPC, which is based on older assumptions). The concentration in drinking water that would lead to an adult exposure of 500 mrem/yr via ingestion is about 11,500 μCi/m³, or 4 times the MPC.

There are two main pathways by which tritium in a fusion reactor could leak to the environment during normal operation. The first is through the heat exchangers into the steam system, from which the tritium can escape into the condenser coolant and thus into the environment (as liquid HTO). Assuming all the rejected heat from a 2.5 GWt fusion powerplant operating at 0.7 load factor and 40% efficiency is carried off in once-through condenser water that is raised 10 degrees C, the annual throughput of water is 9 × 10^[illegible] cubic meters. If the requirement is that the HTO concentration could not produce a dose greater than 5 mrem per year in an individual taking all his or her drinking water from the condenser discharge (similar to the present standard for LWRs), the maximum permissible annual discharge of tritium in the condenser water is 1.15 × 10^-4 Ci/m³ × 9 × 10^[illegible] m³/yr = 1 × 10^[illegible] Ci. This is about [illegible] Ci/day, or about 1 part in 10^[illegible] of the 2.5 × 10^[illegible] Ci of tritium in our "[illegible]" conceptual design. Control of tritium to 1 part in 10^[illegible] per day requires an improvement of about three orders of magnitude over the tritium control achieved in LWRs today, and an improvement of 1 to 2 orders of magnitude over that envisioned for commercial LMFBRs. Typical fusion reactor designs deal with the problem by making the fuel extraction system (which removes tritium from the primary coolant) large enough and efficient enough to hold the T concentration in the primary coolant to very low levels; this low T concentration then limits the diffusion of T into the intermediate coolant loop (if any), and from there into the steam system. Design values for T release by this pathway on the order of [illegible] to [illegible] Ci per day per GWt have been reported [illegible].

The second pathway for tritium escape is diffusion through the various containment-system boundaries, eventually to escape into the air around the plant as HT or gaseous HTO. This pathway generally has been regarded as easier to control, and the resulting emissions predicted to be smaller. Approaches used include separating hot T inventories from cold ones and making every design effort to minimize the former, surrounding hot T areas with cold metal walls, and employing copper, aluminum, or ceramic coatings as diffusion barriers (3, 17, 18). The most promising way to minimize the hot tritium inventory seems to be breeding in solid lithium compounds in a helium-cooled blanket. With this approach, inventories in blanket and coolant (combined) as low as 10^4 Ci/GWe have been said to be possible (19).

The tritium inventory most difficult to reduce seems not to be the inventory in the breeding medium, however, but rather the inventory associated with recycling tritium that has been injected as fuel but escapes from the reaction region without burning. The lower the fractional burnup per pass, the more severe this problem. (Simply the reserve to permit continued operation if the cycling system for unburned tritium malfunctions must be about $1.4 \times 10^6/f$ curies per GWt-day, where f is the fractional burnup per pass.) A tritium handling system for a mirror fusion reactor has been described with a design inventory of 2×10^7 Ci/GWe for the entire plant, but no reserve for malfunctions is included in that figure (20).

In addition to releases from the plant, routine exposure of workers inside the fusion plant to tritium is also a potential concern. The occupational MPC for HTO in air is 5 μCi/m^3, and U.S. ERDA guidelines call for using levels of 20% MPC as design guidelines. It is not clear whether this guideline can be met in a CTR; if it cannot, working shifts may have to be restricted to less than 40 hours per week or protective suits (to prevent skin absorption) and masks may have to be used (20).

Of course, most of the technologies envisioned to provide the extraordinary degree of tritium control required in fusion reactors remain to be proven in practice. How difficult and how expensive it will be to keep track of tens of kilograms of tritium to an accuracy of 1 part in 10^6 per day, in the real world of leaky valves, faulty seals, cracked diffusion barriers, and so on, will not really be known until we have tried it.

In addition to T, radiation hazards of possible consequence in routine operation of fusion power plants are posed by the activation products in the reactor structure, by the energetic fusion neutrons themselves, and by strong magnetic fields used to confine the fusion plasma.

With respect to activation products, it is widely supposed that these will remain for the most part fixed in place in the structure until it is removed for reprocessing and/or disposal. Some of the materials involved form oxides that are much more volatile at operating temperatures than the elemental forms, however, and the extent to which losses of these volatile oxides will contribute to releases of radioactivity from the plant and to occupational exposures inside needs closer investigation. Maintenance of a nonoxidizing atmosphere in contact with the activated structure might be necessary. It must also be noted that, even when fixed solidly in place, those activation products that emit penetrating gamma rays or neutrons (from γ,n reactions) pose a potential hazard to workers in and near the plant.

Since the objective in DT fusion is to harness the 14-MeV fusion neutrons for tritium breeding and thermal energy conversion, there is strong incentive to minimize escape of neutrons from the blanket region. It is also essential to protect the superconducting magnets from high neutron fluxes. Nevertheless, the great penetrating power of the fusion neutrons and the complex geometry of fusion-reactor interiors will make complete shielding difficult in the immediate area of the reactor. Sufficient shielding can be incorporated into the reactor building itself to reduce the neutron dose outside to any desired level, however. Thus neutron exposure will be an occupational hazard, but presumably not a public one.

Magnets for typical Tokamak reactors would produce fields that extend far beyond the reactor -- 500 meters to drop to 1 gauss in UWMAK-I, for example (10). Prolonged exposure of fusion workers to magnetic fields of some tens of gauss is to be expected and brief exposures to much higher fields are possible. The physiological consequences of prolonged exposure of humans to strong magnetic fields are not known. At exposures that will be encountered routinely in fusion, such effects may be nonexistent or negligible or they may be significant, and more research on the question is needed (3). At some expense, possibly significant, the magnetic field intensity outside the reactor building could be reduced by means of shielding with magnetic materials or partial cancellation with additional magnets arranged for this purpose.

Accidents

The risk from accidents at nuclear facilities is the integral or sum, over all possible accidents, of the probability of occurence times the consequences of these accidents. As the debate over fission power has shown, significant uncertainties and even controversies attend every step of the assessment of this risk: the identification of the possible accidents, the estimation of their probabilities, and the evaluation of the potential damages. Since there is no operating experience nor even a firm engineering design for fusion power plants, the difficulty of accident analysis is even greater than is the case for fission. At most one can identify some potential problem areas, estimate very roughly the consequences of hypothetical events, and make some crude comparisons with fission.

Relevant to the identification of possible accidents and assessment of their probabilities are the amounts of stored energy in various parts of fusion reactor systems and the pathways potentially available for the release of such energy.

The amounts of energy stored in a Tokamak reactor based on recent conceptual designs are summarized in Table 3.

Rapid release of the nuclear energy represented by the fuel contained in the plasma at any given time seems exceedingly unlikely on the basis of present knowledge of plasma behavior. It is conceivable that malfunctions could produce a temporary increase in reaction rate by virtue of increased temperature or magnetic field, but the delicate balance of conditions required for plasma containment means that the end result of any departures from normal operating conditions would be rapid quenching of the reaction due to loss of plasma to the walls. If somehow the entire quantity of fuel in the plasma did react, the less than hundred gigajoules evolved would raise the blanket temperature only about 100°C (6).

The kinetic energy of the hot plasma is about two orders of magnitude smaller than the potential nuclear energy. If an instability were to cause the entire hot plasma to be deposited on a small section of the vacuum wall, a local burn-through could result (3, 6). Such an event would naturally be disruptive and expensive for the operators of the reactor, but it could only produce serious external consequences if it led to a major lithium fire, as discussed below.

A very substantial quantity of energy, hundreds of gigajoules, is stored in the superconducting magnets that confine the fusion plasma. Concern is sometimes expressed that the sudden release of this energy owing to a magnet transition from the superconducting to the normal state would represent an important accident pathway for fusion reactors, and considerable analysis of the question has been done. It seems a relatively straightforward matter, however, to design magnets incorporating normal conductors as alternate current paths, along with adequate energy sinks for the associated joule heating, in such a way that an explosive energy release from a magnet "going normal" is precluded (21).

It will remain true, of course, that large superconducting magnets in operation are subject to very large forces (on the order of 10^5 tons), so that catastrophic structural failure perhaps cannot be entirely ruled out. Such a failure could produce energetic missiles, raising the possibility of severe damage to other reactor components, penetration of containment structures, and initiation of lithium fires.

Energetic missiles, with these same possible consequences, could also be produced by sudden vacuum-system failure, by helium overpressure in the magnet cooling system, by "external" events such as earthquakes, tornados, aircraft impact and sabotage, and of course by combinations of these pathways.

An important accident pathway for all nuclear systems is loss of coolant - loss of coolant flow. Calculations made for the UWMAK I Tokamak conceptual design indicate that complete loss of coolant flow during thermonuclear burn, accompanied by failure to shut down the fusion reaction, would cause the first wall to reach a temperature of 600°C in about 10 seconds; embrittlement from formation of helium bubbles in the metal, which occurs around 650°C, could then lead to failure of the wall, release of lithium into the vacuum chamber, and consequent quenching of the fusion reaction (3, 10). Like so many other fusion accident pathways considered here, this one would be disruptive and expensive, but not catastrophic unless secondary events produced a major fire and/or breach of containment.

Loss of the coolant itself (as opposed to mere loss of flow), as could occur owing to pipe breaks, would produce the same result as loss of flow somewhat more rapidly, again assuming that the fusion reaction were not immediately shut down. If, on the other hand, the reaction is shut down, the concern becomes the radioactive afterheat that results from activation products in the first wall. The initial afterheat power densities in the first wall at shutdown fall in the range of 0.5 to 1.0 w/cm^3 for the main alternative structural materials (22), and the initial adiabatic temperature rise in a Tokamak system has been calculated to be on the order of 0.1^{o}C/sec (10). These values are more than an order of magnitude lower than the corresponding figures for fission fuel, and they suggest that heat removal by radiation, conduction and natural convection will suffice to prevent melting of the wall.

The largest source of stored energy in fusion reactor designs relying on liquid lithium for cooling and breeding of tritium is the chemical energy represented by the lithium itself, and for such reactors a lithium fire -- whether initiated by internal or external events -- may well represent the "maximum hypothetical accident". Lithium reacts vigorously and exothermically both with air and with water; like sodium, it reacts also with concrete (actually, with the water liberated from concrete by endothermic dehydration). Although the kinetics of these reactions are not well established experimentally, calculated maximum flame temperatures for both the lithium-air and lithium-concrete reactions are in the range of 1,800 to 2,500^{o}K (22). These temperatures are below the melting points of refractory metals, such as niobium and TZM (titanium-zirconium-molybdenum), that might be used in fusion reactor structures, but above the melting points of other potential structural materials such as series 300 stainless steels. The refractory metals, although they would not melt, could be rather rapidly consumed at such temperatures by formation and volatilization of their oxides (22). The high temperatures and large energy releases potentially associated with lithium fires therefore pose the two-edged possibility of (a) breaching multiple containment barriers between the reactor core and the public and (b) augmenting the volatile tritium inventory that could escape through such breaks by converting activation products and toxic nonradioactive metals to volatile form.

The value of increasingly detailed safety analyses at the early stages of design, of course, is that the designs can then evolve to cope with the most serious accident pathways that are identified. The apparent flexibility of fusion in this respect is considerable, especially since passive systems seem capable of handling most if not all of the stored energy sources. The use of liquid lithium as a coolant and breeding medium for tritium, which produces the largest stored-energy threat in many fusion reactor designs, has of course been questioned. Unfortunately, the alternatives are not without their own difficulties. Use of helium as a coolant in conjunction with breeding in lithium solids, for example, virtually requires the use of beryllium as a neutron multiplier; this material is extremely toxic, thus producing additional threats to occupational and public health, and it is scarce and expensive. Use of flourine-lithium-beryllium molten salt (Flibe) as an alternative coolant and breeding material, on the other hand, leads to materials-compatibility problems and to the production of a particularly dangerous form of hydroflouric acid (wherein the hydrogen is tritium and the flourine is 2-hour half life flourine-18). Clearly, much additional work will be required to determine how much the *apparent* flexibility of fusion with respect to coolant and breeding media can *actually* be exploited to maximize safety.

Notwithstanding the possibility of making the frequency of accidents very low, it is important to understand the consequences that could occur in the most severe events (including acts of war, sabotage, natural disasters, and accidents that exceed the design capabilities of the system). As an initial step in such a "worst-case" analysis, I have used essentially the consequence model of the Reactor Safety Study (RSS) of the U.S. Nuclear Regulatory Commission

(23) to estimate the "critical dose" to bone marrow resulting from a release of 10^8 curies of tritium oxide under adverse meteorological conditions. The critical dose, as the concept is used in the RSS, means all the dose received in the first eight days and half the dose received from the eighth through the thirtieth day; it is said to be the most relevant figure for estimating the incidence of early fatalities and, to some extent, early injuries. One hundred megacuries represents 40 percent of the tritium inventory considered in Table [illegible] Whether the release of so large a quantity of tritium at one time, and all as the oxide, is actually credible is debatable, but it provides a basis for comparison with calculated fission-reactor accidents releasing a similar percentage of many of the fission products. Figure 1 shows the critical dose to bone marrow plotted versus area over which a given dose is exceeded for the 10^8 Ci HTO release and for the fission-reactor accident denoted PWR-1 in the RSS. (PWR-1 releases 40 percent of the cesiums, rubidiums, and telluriums, 70 percent of the iodines, 90 percent of the noble gases, 5 percent of the strontiums and bariums, and 0.5 percent of the actinides in a 1 GWe LWR with core burnup averaging 17,600 MWd per metric ton.) The same models and assumptions were used in calculating both cases: gaussian plume model as in RSS, with building wake effects but no thermal plume rise, ground-level release, Pasquill F atmospheric stability with 1.0 m/s mean wind, dry deposition velocity of [illegible] m/s. As can be seen from the figure, the fission release delivers the LD_{50} ([illegible] to [illegible] rem, depending on assumptions about extent of medical care) over an area of roughly 13 km², the fusion release over 1.1 km². At a population density of 100 persons/km², these results correspond very roughly to the order of 1000 early deaths in the fission release and 10 early deaths in the fusion release. In view of the many uncertainties that plague attempts to calculate absolute numbers of fatalities with these crude sorts of models (24), the most important result here is the relative numbers — a factor of about 100 in favor of fusion.

A few further qualifications are in order. First, release of 0.5 percent of the actinides in the fission-reactor accidents considered in RSS made a very small fractional contribution to the calculated early fatalities but a large fractional contribution to calculated long-term cancer incidence (23, Ch. 13). This result suggests that comparison of long-term casualties from fission and fusion releases (which I have not yet done), might show a larger advantage to fusion than the factor of 100 computed here for early fatalities. Second, the release fractions used in the present comparison could be unrealistic in several ways. Tritium inventories in fusion reactors might be reduced by clever designs, reducing the conceivable consequences of a worst-case release. But, if any significant fraction of fusion activation products could be released in an accident, the calculated consequences could be worse than given here for tritium alone (This is reasonably clear from the BHPs in Table 2.) If actinide releases in LMFBR accidents could be greater than the RSS assumed for LWRs, this, too, could change the comparison. These matters need further investigation.

Radioactive Wastes

The presence of activation products of long half-life means that fusion will not be entirely free of the problem of radioactive-waste management, with which the fission power community has long been struggling. The major advantages that have been claimed for fusion with respect to radioactive wastes are: (a) the flexibility to tailor the design and the choice of structural materials exposed to neutrons with the aim of minimizing production of long-lived activation products (to be contrasted with the case of fission, where the size and character of the waste burden is largely determined by the unchangeable physics of the fission process itself), and (b) the immobilization of the activated material in the solid structure of components made of refractory alloys (reducing the chance of escape into the environment). It is possible, however, that flexibility in materials choices will prove illusory (at least for some time to come), if problems with neutron damage, loss of strength at high temperatures, fabricability, weldability, and so on are not solved for the low-activation materials. Whether activation products in fusion reactor structures will prove less mobile than fission products that have been embedded for disposal in a ceramic matrix remains to be verified in detail. (There seem to be significant uncertainties in both cases.) For activated fusion structures that do not have to be reprocessed to recover scarce materials (to be contrasted with fission breeders, whose economic viability requires fuel reprocessing), the smaller need to handle the radioactive material will be an advantage.

Table 4 shows the BHPs with reference to releases to water for radioactive wastes from a Tokamak fusion reactor and an LMFBR, normalized to 1 GWe-yr of electricity production. The main structural material in the fusion reactor is 316 stainless steel. No credit is taken in the LMFBR for recycling of actinides other than uranium and plutonium. Fusion has an advantage in this comparison that varies between 1 and 2 orders of magnitude during the span of time out to 100 years. Between 1000 and 10,000 years fusion and fission do not differ significantly, but after 100,000 years fusion's margin increases again. If vanadium-titanium alloy can be used in place of 316 stainless steel in the fusion reactor, one gains an additional factor of 1,000 reduction in the BHP by 20 years, and by 100 years the material is innocuous (less radioactive than average rock). This advantage of V-Ti in decay time is so big that it must be considered qualitative, and no other low-activation candidate material loses its hazard as rapidly. Whether V-Ti can meet the other demanding requirements of fusion application therefore deserves the closest scrutiny.

Misuse of nuclear materials

The advent of commercial fission power and the associated increase (both real and forecasted) in accessibility of plutonium and enriched uranium has engendered considerable concern about the possible misuse of these materials as weapons. To understand whether fusion power will have any analogous liabilities, it is important to clarify several aspects of the general threat by distinguishing (a) production of weapons by governments versus production by subnational groups, and (b) explosive weapons versus radiological weapons.

Lack of suitable fissile materials and the difficulty of getting them have been major factors in limiting the international spread of fission bombs; the knowledge of how to produce a fission bomb once the material is in hand has been more accessible than the material itself (25), and this means that the spread of material (or the technology for getting it) as a consequence of the spread of fission power has changed the situation in a qualitative way. But fusion bombs are more difficult to construct than are fission bombs, so much so that obtaining the fusion fuels (say, tritium) is, relative to the fission case, only a small part of the task (2). Hence the spread of tritium by fusion power presumably does not contribute much to the spread of fusion bombs. There is a cross-connection between fusion and fission, however: the neutrons produced by fusion reactors could be used to produce fissile material for fission bombs. This cannot be done without the consent and extensive cooperation of the operators of the fusion reactor, so it is a problem at the level of undesirable activity by governments or very large corporations, not smaller groups.

Tritium could be used as a radiological weapon by terrorists or gangsters who acquired it, just as plutonium from fission fuel cycles could be used.

Some of the data required to assess the relative magnitudes of these threats are summarized in Table 5. The MPCs for plutonium isotopes are much lower than that of tritium (measured as Ci/m^3), but the specific activity of tritium (Ci/gram) is much higher than for plutonium. The result is that the BHPs associated with the inventory per GWe or flow per GWe yr of tritium and reactor-grade plutonium work out as follows: tritium is less dangerous than plutonium by 2 to 5 orders of magnitude with respect to contamination of air, but the two are approximately equal with respect to contamination of water. Some degree of consensus appears to be emerging that the MPCs for plutonium are too high by a factor of 5 to 10 (in a relative sense, the comparison being in this case with radium) (76), and there is some reason to think the MPCs for tritium may be too low by factors of 2 to 4 (see discussion above). Incorporation of such correction factors, if they are validated, would change the foregoing comparison to make tritium less dangerous than plutonium by one order of magnitude with respect to contamination of water and to give tritium an advantage of 3 to 6 orders of magnitude with respect to contamination of air. In terms of potential access to the material by malefactors, fusion has an advantage because there is no need to transport tritium beyond that needed for initial inventories of new reactors.

Advanced fuel cycles

Fusion reactions other than D-T require higher reactant energies and better confinement to achieve energy breakeven. If advanced technology permits attainment of the needed conditions, these more difficult reactions could offer important environmental advantages. Of the advanced reactions (including H-Li^6, D-D, D-He^3, and H-B^{11}), the least difficult is D-D. The D-D reaction chain (which includes D-T and D-He^3 reactions on the T and He^3 produced as reaction products of D-D) produces fewer and less energetic neutrons than pure D-T, although the neutron activation does not fall as much as one might expect — by 15 to 75 percent, depending on the structural material (27,28). Perhaps the greatest advantage of the D-D cycle is that it would remove the necessity to use neutrons to breed tritium from lithium. This means that the complexity of the equipment surrounding the plasma could be considerably reduced, and the array of candidate materials for use there would be broadened by relaxation of the neutron-economy constraints present when tritium must be bred. The total tritium inventory in the reactor could be reduced below that in D-T reactors by a factor of perhaps 3 to 10 (28). Other advanced reactions have the potential for greater reductions in neutron activation and tritium inventory, particularly in "two-component" systems where the rates of the neutron-free reactions can be enhanced by tailoring the energy distributions of the different reactants. It is problematical whether confinement technology will ever be good enough to make these reactions practical, however.

Conclusions

Overall, the potential environmental and safety advantages of [illegible] fusion compared to fission appear appreciable. These include lower biological hazard potentials in the radioactive inventories in the reactors and in long-lived waste, lower radioactive afterheat, very limited energy release in reactivity accidents, and significant advantages with respect to misuse of nuclear materials.

Fusion's problems are not negligible, however, and large advantages compared to fission are not automatic. Legitimate questions of great interest are (a) how much of fusion's potential advantage will be realized in practical reactors, especially early ones? (b) how much can the presently evident potential be increased by ingenious new ideas and/or advanced fuel cycles?

It is clear in any case that converting fusion's environmental potential into practical reality will require that high priority be given to environmental characteristics throughout the process of fusion reactor design and engineering. (Greater emphasis on research to determine whether low-activation alloys such as V-Ti can meet the technological requirements of fusion is an essential early step.) If, on the other hand, it is simply assumed that environmental characteristics will take care of themselves, or be taken care of by add-ons after the basic reactor has been designed, the result could easily be fusion reactors in which many of the principal reasons for developing fusion at all have been sacrificed in pursuit of other engineering and economic criteria.

Notes

1. Much of the information upon which this analysis is based was assembled as part of a workshop on environmental characteristics of fission and fusion carried out in 1975 and 1976 under the auspices of the International Institute for Applied Systems Analysis. The principal participants included the author, G. L. Kulcinski (University of Wisconsin), G. Kessler (Kernforschungszentrum Karlsruhe), and W. Haefele (I.I.A.S.A.). The complete output of this workshop, including some contributions by Soviet scientists not available at this writing, will be published as an I.I.A.S.A. report. The responsibility for the present formulation is the author's.

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Table 1

Radioactive Inventories of Fission and Fusion Reactors

Megacuries per GWe (2.5 GWt) versus time after shutdown

	LMFBR Fission	316SS Fusion	V-Ti Fusion
at shutdown			
fission products/tritium	11,200	250	250
structural activation	100	2700	3100
coolant activation[a]	110	<75[b]	<75[b]
actinides	4000	--	--
10^4 sec (2.77 h) after shutdown			
fission products/tritium	5,200	250	250
structural activation	83	1500	150
coolant activation	96	<60[b]	<60[b]
actinides	1800	--	--
1 day after shutdown			
fission products/tritium	2,900	250	250
structural activation	70	1200	130
coolant activation	37	<50[b]	<50[b]
actinides	1400	--	--
30 days after shutdown			
fission products/tritium	920	250	250
structural activation	53	600	11
coolant activation	1	<40[b]	<40[b]
actinides	70	--	--

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[a] Assumes pool-type LMFBR and liquid Li coolant in CTR. Loop-type LMFBR has 4-fold smaller coolant activation. Helium cooled CTR has negligible coolant activation 1 sec after shutdown.

[b] Detailed calculations for fusion coolant activation not complete.

Source: IIASA Workshop (see Note 1).

Table 2

Comparison of Biological Hazard Potentials with Reference to Accidental Releases to Air. Million cubic kilometers of air per GWe (2.5 GWt) versus time after shutdown.

	LMFBR Fission	316SS Fusion	V-Ti Fusion
at shutdown			
FP/tritium	>2900[a]	1.25	1.25
structural activation	55	390	68
coolant activation	26	NA	NA
actinides	13,500	--	--
10^4 sec (2.77 h) after shutdown			
FP/tritium	2700	1.25	1.25
structural activation	55	360	45
coolant activation	24	NA	NA
actinides	13,400	--	--
1 day after shutdown			
FP/tritium	2300	1.25	1.25
structural activation	54	370	38
coolant activation	12	NA	NA
actinides	13,300	--	--
30 days after shutdown			
FP/tritium	1100	1.25	1.25
structural activation	47	200	15
coolant activation	5	NA	NA
actinides	13,200	--	--

NA = not available

[a] 35 isotopes (omits much short half-life activity)

Source: IIASA Workshop

Table 3

Stored Energy in a 1 GWe Tokamak Fusion Reactor
(1 significant figure)

Energy Form	GigaJoules
Chemical energy in liquid lithium	60,000
Magnetic field energy	300
Complete fusion of fuel in plasma	70
Pressure-volume work in vacuum	20
Kinetic energy in plasma	$\lesssim 1$

Sources: 6,10

Table 4

Biological Hazard Potentials of Long-Lived Wastes with Reference to Releases to Water. Cubic kilometers of water per GWe-yr versus time after shutdown.

	Fusion 316SS activation	LMFBR fission products	LMFBR actinides[a]
1 year	1400	10,000	100
10 years	49	3600.	28
30 years	9.0	2100.	24
100 years	2.7	330.	20
1000 years	1.1	0.020	4.7
10000 years	0.9	0.018	0.52

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[a] 1% of plutonium and uranium and 100% of other actinides from discharged fuel

Source: IIASA Workshop

Table 5. Radiological Hazards of Plutonium and Tritium (Quantities normalized where appropriate to 1 GWe of capacity)

	Plutonium	Tritium
Inventory outside blanket (kg)	900	25
Annual flow outside reactor (kg)	1500	32[a]
MPC_{air} (Ci/km^3)		
--insoluble ^{239}Pu, HT or T_2 gas	0.007	40.000
--soluble ^{239}Pu, HTO vapor	0.00006	200
BHP (km^3 of air) per gram of:		
--pure ^{239}Pu, elemental T	63 to 1000	0.25
--reactor Pu[b], T in HTO	300 to 5000	50
BHP/GWe-yr[c] (10^6 km^3 of air per year)		
--best case[d]	450	0.008
--worst case[e]	7500	1.6
BHP/GWe[f] (10^6 km^3 of air)		
--best case[d]	270	0.006
--worst case[e]	4500	1.25
MPC_{water} (Ci/km^3 for soluble forms)	5000	3,000,000
BHP (m^3 of water) per gram of:		
--pure ^{239}Pu in soluble compound	12,500	
--reactor Pu in soluble compound	62,500	
--pure T in HTO		3,300,000
BHP/GWe-yr[c] (km^3 of water per year)	94	110
BHP/GWe[f] (km^3 of water)	56	83

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a. At breeding ratio = 1.25.

b. Contains Pu-238,239,240,241,242.

c. Based on flow outside reactor.

d. Reactor-grade Pu dispersed in insoluble form, tritium dispersed as T gas.

e. Reactor-grade Pu dispersed in soluble form, tritium dispersed as HTO vapor.

f. Based on inventories outside blankets.

Figure 1

CRITICAL DOSE TO BONE MARROW VS AREA FOR HYPOTHETICAL FISSION AND FUSION ACCIDENTS